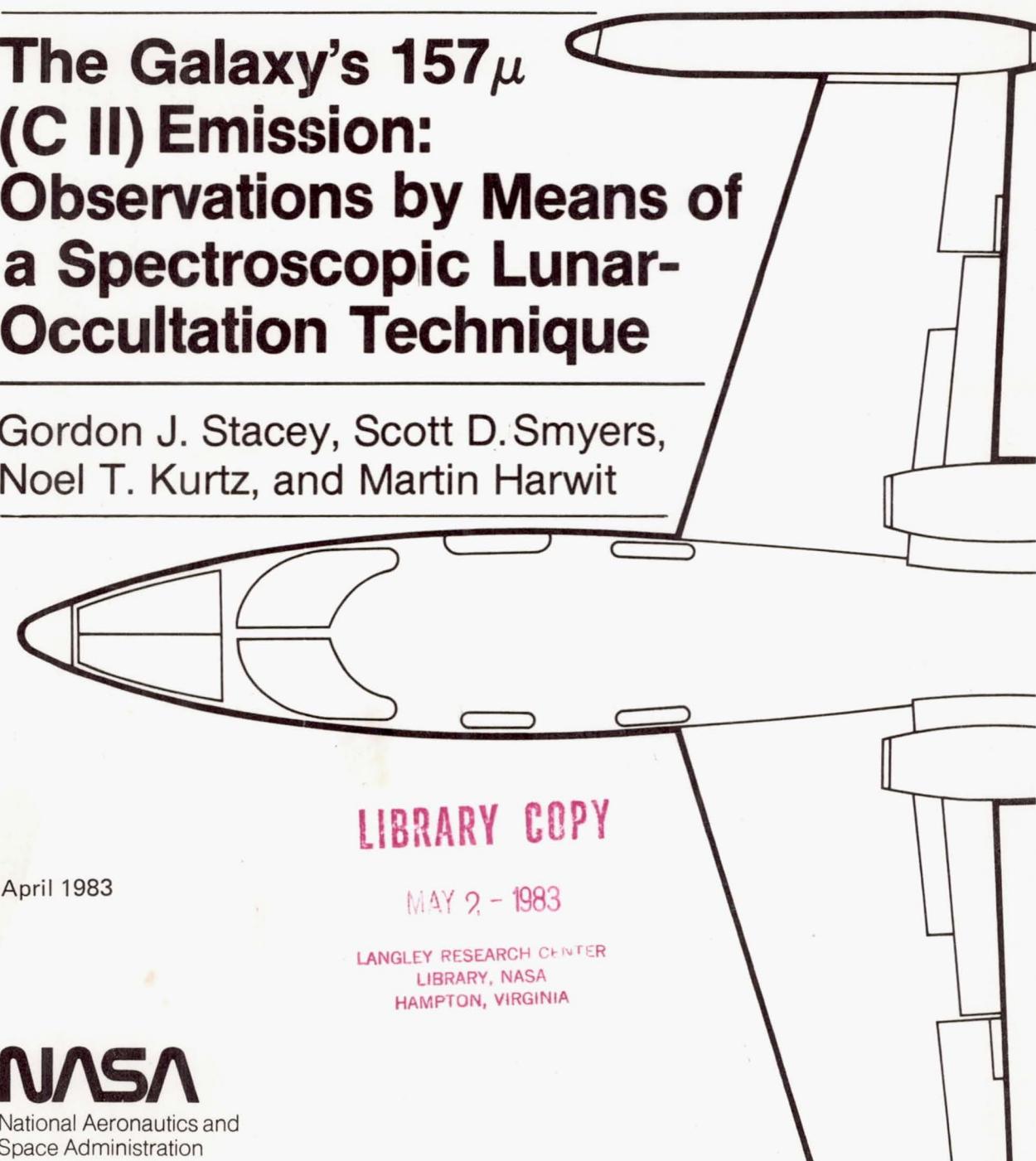


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THE GALAXY'S 157μ [C II] EMISSION: OBSERVATIONS BY
MEANS OF A SPECTROSCOPIC LUNAR-OCCULTATION TECHNIQUE

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Galaxy; fine-structure transitions.

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ABSTRACT

We have obtained a first, direct estimate of Galactic [C II] 157μ , fine-structure emission. At a Galactic longitude of 8° , the peak power observed in a $7' \times 7'$ field is $\sim 5 \times 10^{-9}$ Watt $\text{cm}^{-2} \text{sr}^{-1}$. The method used to detect this radiation involved chopping against the cold side of the Moon. In the next few years, higher resolution far-infrared spectroscopy should enhance the usefulness of occultation techniques for detecting faint, diffuse line emission.

I. INTRODUCTION

For over a decade it has been postulated that the general interstellar medium close to the Galactic plane cools itself principally through line emission at 157μ in a fine-structure transition of singly ionized carbon.

An estimate of the cooling rate attained through this process was published by Pottasch, Wesselius and van Duinen (1979). They observed the strength of ultraviolet absorption lines originating from the upper fine-structure level, $^2P_{3/2}$, and estimated from this, the column density of carbon ions in that level. This allowed them to compare the $C+(^2P_{3/2})$ column density to the column density of neutral and ionized hydrogen along the same line of sight. Knowing the Einstein coefficient $A_{21} = 2.4 \times 10^{-6} \text{ sec}^{-1}$ for spontaneous emission of the 157μ line, these authors then estimated the cooling rate provided by this transition per hydrogen atom (neutral or ionized). This procedure was carried out for nine separate clouds all of which yielded a 157μ cooling rate remarkably close to $10^{-25} \text{ erg sec}^{-1}$ per hydrogen atom.

It appeared to us important to attempt to observe the 157μ radiation directly, to obtain a surface brightness for the Galactic plane in the radiation

from this line. The prime difficulty with such an attempt is the extreme width ~ 10 over which this radiation might be expected to extend. Diffuse radiation extending over such wide regions is difficult to observe in the far infrared: The radiation to be observed must be chopped; but even the chopper on NASA's Lear Jet, capable of chopping across nearly 15 minutes of arc, did not appear to have a large enough throw to chop between the Milky Way and a point sufficiently far removed to provide a zero intensity level required for comparison. We therefore chose to use a lunar occultation technique.

The Moon crosses the Galactic plane twice a month. One of these times it generally crosses the plane at a distance of 5° to 10° from the Galactic center. By choosing one of these crossing times, and following the Moon as it occults the Milky Way, it is possible to chop between the Moon and Milky Way, using the Moon as a source from which no line emission at 157μ is to be expected.

II. OBSERVATIONS

Our observations were carried out with the far-infrared, liquid-helium-cooled grating instrument described earlier (Houck and Ward 1979). The field of view of the instrument was widened, to $7' \times 7'$ which increased the amount of radiation that could enter

the system, but also degraded our resolving power to $\lambda/\Delta\lambda \sim 100$.

Observations were carried out during a number of flights, in order to gain familiarity with potential difficulties, particularly the problem of dealing with the large dynamic range required to detect the faint 157μ line-radiation in the presence of a strong lunar continuum. The principal observations to be discussed here took place at the times and dates given in Table 1. The table also provides a range of Galactic latitudes and longitudes observed during these runs.

Table 1. Dates, Times and Galactic Coordinates of Observations

<u>Date</u>	<u>Time</u>	<u>l^{II}</u>	<u>b^{II}</u>
2/18/82	$16^{\text{h}} 55^{\text{m}}$	7.9°	$-3.8'$
	$17^{\text{h}} 30^{\text{m}}$	8°	$-15'$
2/19/82	$19^{\text{h}} 30^{\text{m}}$	14.5	-12.5
	$20^{\text{h}} 30^{\text{m}}$		

On the day of the Galactic-plane observations the Learjet was taken north and east of Moffett Field, California, to provide a flight of maximum duration for observations of the source. A northern latitude was required to permit observations of the Moon which otherwise would have been located too high in the sky for the telescope to follow. The eastern starting position permitted a long westerly observing leg to view the Moon, which was almost directly south in the sky. Directly following the last spectral run the plane landed for refuelling, before returning to Moffett Field.

The flight provided us with a series of spectra which were divided into five parts, according to galactic latitude (Table 2).

TABLE 2

Intensities for Galactic CII Emission

b	Spectra	$I(W \text{ cm}^{-2}\text{sr}^{-1} \times 10^9)$
-3.8'	#1	5.1 ± 1.1
-5.4'	#2 - 4	3.1 ± 1.0
-7.8'	#5 - 8	$1.2 \pm .7$
-10.8'	#9 - 12	$0.4 \pm .7$
-13.8'	#13 - 16	-0.3 ± 1.3

We chopped against the dark side of the Moon (Fig. 1) using the Moon's cusp as a reference point for offset

guiding. Two different detectors were used, viewing slightly displaced portions of the spectrum. The total spectral range covered was $154.8\mu < \lambda < 160.2\mu$. Sixteen spectra were obtained with each detector. The noise figures cited are one standard deviation from the mean. Our main source of noise was the guiding jitter in observing the Moon. Fig. 2 displays the data graphically and shows the width of our beam. The calibration procedure we followed made use of two independent calibration runs. The first calibrator consisted of the observations from February 19, 1982. The second consisted of a summation of the last four spectra taken on the 18th, the date of actual plane-crossing. This second set of data was used because it was obtained on the same flight as the plane-crossing data, and therefore precluded the possibility that subtle instrumental changes might have taken place between flights. Both sets of calibrations yielded practically indentical results, indicating that the 157μ signal had essentially dropped to zero, within our noise estimates, by the time a galactic latitude of $-15'$ had been reached. The Moon was assumed to emit like a 100 K blackbody (Mendell and Low 1970).

The first four sets of spectra listed in Table 2 were calibrated by a weighted average of the two calibration sources. Our weighting function gave priority

to lower noise data. The fifth set of spectra are calibrated only by data from the flight of February 19.

III. DISCUSSION

Two features of the observed 157μ flux bear particular attention: a) The flux is high, and b) it drops rapidly with increasing distance from the plane.

The narrowness of the observed distribution is remarkable; it is so narrow that it could be consistent with a compact source and also could have been directly observed without chopping against the Moon. However, in that case, we could not have been certain of the absence of a more diffuse 157μ component.

A drop over a half height $\Delta b \sim 1/6^\circ$ is rather sharper than one would anticipate on the basis of far-infrared dust emission which provides a measure of the gas-dust distribution, or of gamma-ray emission which generally is well correlated with dark clouds.

Nishimura et al. (1980) have mapped our region at wavelengths between 100 and 300μ . Their maps would suggest that a drop to half-height within $\sim 1/2^\circ$ is more typical. Hart and Pedlar (1976) find the H 166α line intensity to drop by a factor of 3 over a $\pm 0.5^\circ$ latitude span about latitude $b = 0^\circ$ at Galactic longitude $\ell = 25^\circ$. Presumably, this is not an isolated occurrence.

A search through the catalogues of Altenhoff et al. (1970) and Downes et al. (1980) shows no known HII regions at the position we observed. The far-infrared maps of Gispert et al. (1982) and Nishimura et al. show no unusual features in this region, though both the 2μ data and the CO ($J=1 \rightarrow 0$) emission show peaks at $\ell_{II} = 8^\circ$ (Ananth and Nagaraja 1982 and Scoville and Solomon 1975).

Solomon and Sanders (1980) have constructed high-resolution CO ($J = 1 \rightarrow 0$) maps of the galactic plane which suggest the presence of a flattened ring containing giant molecular clouds in a region 4-8 kpc from the Galactic Center. Sanders (1982) finds the region around $\ell_{II}=8^\circ$ to be typical of a whole range of longitudes except that there is a minimum at $b = -12'$, where the signal strength is only half as great as at higher and lower latitudes. This might correspond to the sharp signal drop we observe at 157μ . Further observations should tell. Excitation of carbon ions can be induced in collisions either with hydrogen atoms and molecules or with electrons. These three excitation rates must be considered separately.

Dalgarno and McCray (1972) provide an expression for the emission rate of C⁺ excited by electron

collisions. The expected intensity at temperature T is

$$I[T] = L_e[T] \langle n_e^2 \rangle S_e [n_{C^+}/n_e]/4\pi$$

with

$$L_e[T] = 7.9 \times 10^{-20} T^{-1/2} \exp[-92/T] \text{ erg cm}^3 \text{ sec}^{-1}$$

and with S_e , the path length through the clouds of electron density n_e and C^+ density n_{C^+} . At most, one-tenth of the flux we observe can be produced through collisions with electrons, if the overall emission measure detected from the Galactic ridge $< 5000 \text{ cm}^{-6} \text{ pc}$ is not to be exceeded (Shaver 1976).

Impacts with neutral atoms and molecules can more readily account for the 157μ flux. Launay and Roueff (1977) have calculated the emission rates for C^+ collisionally excited by hydrogen atoms at different temperatures. For gas at a temperature somewhat in excess of 100 K, $L_H[T]$ has a value $\sim 10^{-23} \text{ erg cm}^3 \text{ sec}^{-1}$. For molecular hydrogen, Flower et al. (1977) obtain a value roughly half as large as that for atomic hydrogen.

The [CII] emission most probably would arise at the edges of molecular clouds, since the penetration of ultraviolet radiation into dense molecular clouds

is limited to a column density of the order $N_H \sim 3 \times 10^{21} \text{ cm}^{-2}$. Along half of this column depth the hydrogen ceases to be atomic and becomes predominantly molecular.

The observed 157μ intensity is then given by:

$$I[T] = (L_H [T] \langle n_H^2 \rangle + 2L_{H_2} [T] \langle n_{H_2}^2 \rangle) S_H \left(\frac{n_C^+}{n_H} \right) / 4\pi$$

where the factor of 2 arises since $\frac{n_C^+}{n_{H_2}} = 2 \frac{n_C^+}{n_H}$.

Taking $\frac{n_C^+}{n_H} = 3.3 \times 10^{-4}$ we obtain the observed peak

intensity if $(\langle n_H^2 \rangle + \langle n_{H_2}^2 \rangle) S_H = 2 \times 10^{26} \text{ cm}^{-5}$, for $L_H = 10^{-23} \text{ erg cm}^3 \text{ sec}^{-1}$. If the clump densities are $n \sim 1000 \text{ cm}^{-3}$, both for atoms and molecules, we obtain a mean luminosity of $\sim 2 \times 10^{-24} \text{ erg sec}^{-1}$ for each hydrogen atom in any form, and column densities $N_H \sim 10^{23} \text{ cm}^{-2}$, and $N_{H_2} \sim 10^{23} \text{ cm}^{-2}$. The molecular hydrogen column density agrees with that calculated from CO ($J = 1 \rightarrow 0$) measurements at $\lambda = 8^\circ$, $b = 0^\circ$ (Solomon and Sanders 1980). A column density $N_H = 10^{23} \text{ cm}^{-2}$ of atomic hydrogen averaged over a pathlength of 30 kpc corresponds to a mean density of 1 cm^{-3} , which is only somewhat higher than the mean neutral hydrogen density computed by Mezger (1978).

Our measured thickness of the layer below the plane corresponds to $\sim 7'$, or 8 pc, at the distance of the CO peak of Solomon and Sanders. Their measurements show that the CO emission is enhanced at negative latitudes near $\ell = 8^\circ$. Thus, taking the full width of an emitting 4-8 kpc ring to be 16 pc is probably an overestimate, but we use it as a first approximation. If the required column densities were uniformly distributed over the 4-8 kpc ring, we would have $\langle n_H \rangle \sim \langle n_H \rangle_2 \sim 4 \text{ cm}^{-3}$ and a total mass of order $7 \times 10^8 M_\odot$. The associated 157μ luminosity is $\sim 5 \times 10^8 L_\odot$, corresponding to the mean luminosity $\sim 2 \times 10^{-24} \text{ erg/atom}$ of hydrogen, a factor of 20 higher than the value cited by Pottasch et al. -- perhaps reflecting different conditions nearer the sun. If the total mass of neutral gas in the Galaxy is considered, this emission per atom is lowered a factor of 10. The 157μ luminosity we observed compares to $2 \times 10^{10} L_\odot$ in far-infrared ($72-196\mu$) continuum emission estimated by Gispert et al., roughly one-third of which lies at wavelengths $\lambda > 100\mu$ (Nishimura et al. 1980). This line-to-continuum ratio is reasonable in view of the large 157μ flux observed in extended regions around M17 and NGC 2024 (Russell et al. 1981, Kurtz et al. 1982): Although complete maps still do not exist for these two HII regions, preliminary data suggest that the line-to-continuum ratio integrated over each entire complex may be of the order of 1%.

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FIGURE CAPTIONS

Figure 1 - Position of the Moon at the time of observations the Galactic ridge, superposed on the far-infrared map of Nishimura et al. (1980). The blown-up portion of the diagram shows position of the beams and direction of motion of the Moon.

Figure 2 - The 157μ [CII] fine-structure line emission observed as a function of latitude Δb , off the Galactic plane. Error bars are one standard deviation from the mean. The cross-hatched strip represents the width of our field of view.

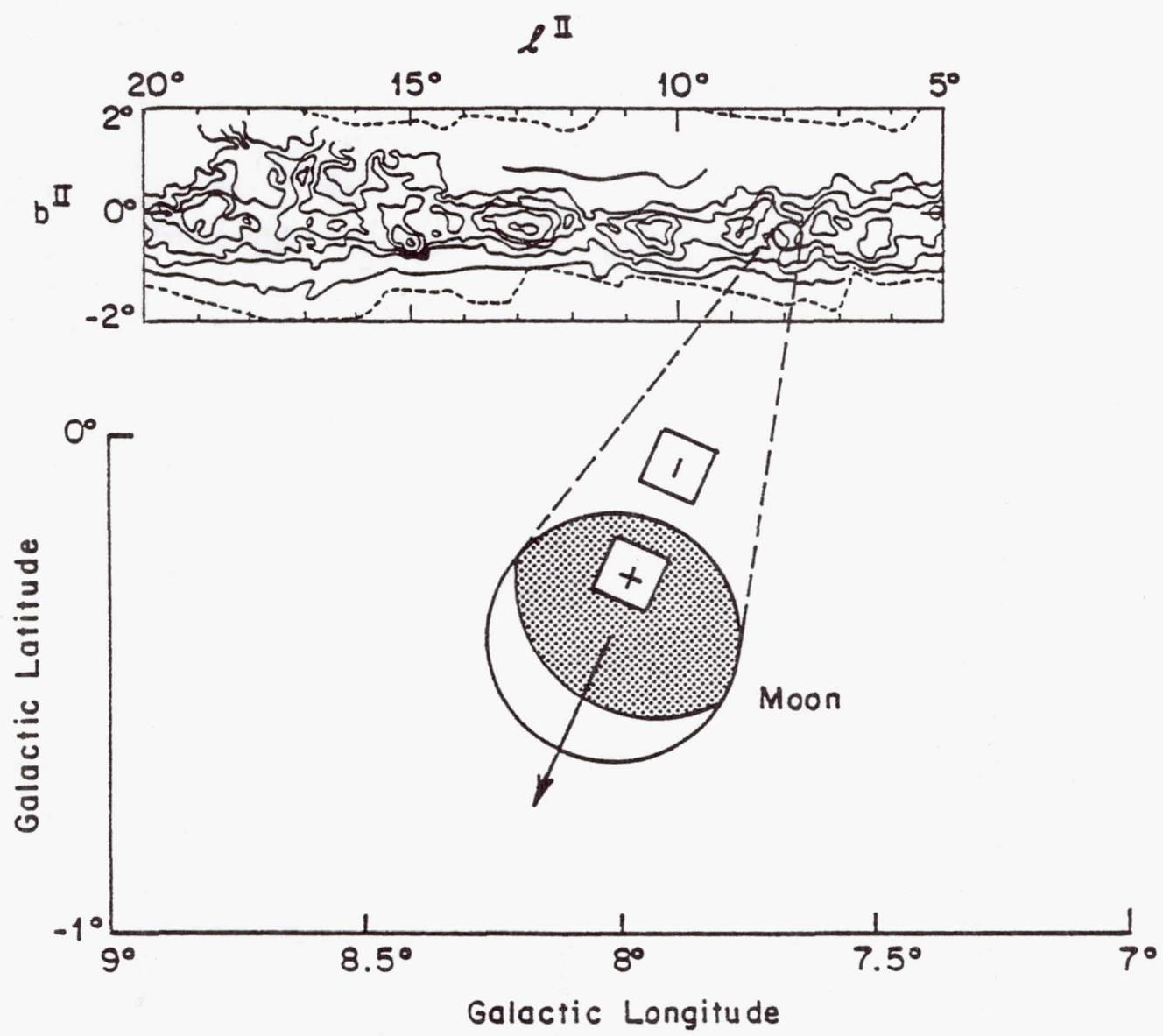


Figure 1

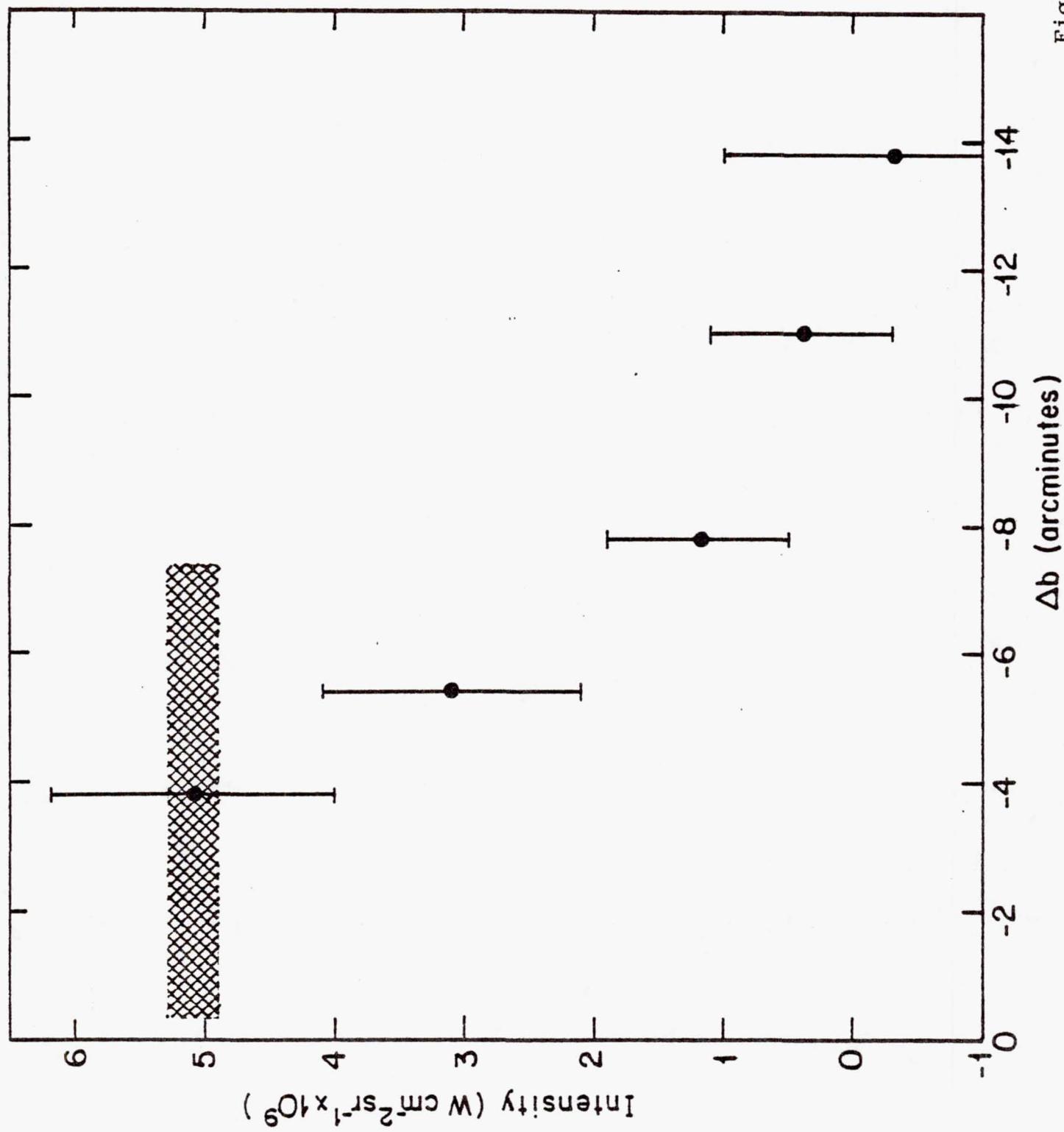


Figure 2

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